Laboratory Verification of the Optical Turbulence Sensor (OTS): Particulate Volume Scattering Function and Turbulence Properties of the Flow

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LONG-TERM GOALS

Our aim is to test a robust and noninvasive measurement of particulate and turbulence for coastal applications.

Our goal is an extensive tank validation of the Optical Turbulence Sensor (OTS). This sensor uses a Hartman optical wavefront sensor to determine turbulence characteristics and to characterize the particulate field. In our configuration the wavefront sensor has been able to quantify simultaneously turbulent and particulate scattering for particles larger >50 μm.

OBJECTIVES

Our laboratory studies were carried out in a well controlled fully turbulent convective tank. The optical measurements have been carried out with a number of neutrally buoyant spherical particles of diameter ranging from between 0.5 and 1000 μm.

We have three main objectives:

Turbulence characterization: in this part of the effort we have compared thermistor (the temperature dissipation rate and the temperature dissipation spectra) and Particle Imaging Velocimetry (PIV) measurements of the turbulent kinetic energy dissipation rate, with concurrent optical OTS measurements of the same variables.

Particle field characterization: we have tested a new Volume Scattering Function (VSF) measurement method where we have used a wavefront sensor (OTS) to calculate large particles (particles larger >50 μm) VSF.

Particle/turbulence interaction: in this part we have carried out simultaneous measurement of the particle VSF, the flow velocity and flow turbulent quantities using OTS. These optical derived parameters were then compared with same parameters obtained using PIV technique (energy dissipation rate, flow speed, flow shear), fast thermistor (temperature dissipation rate, temperature spectra), nephlometer (particle VSF).

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In addition we plan on quantifying of particle transport by coherent turbulent structures.

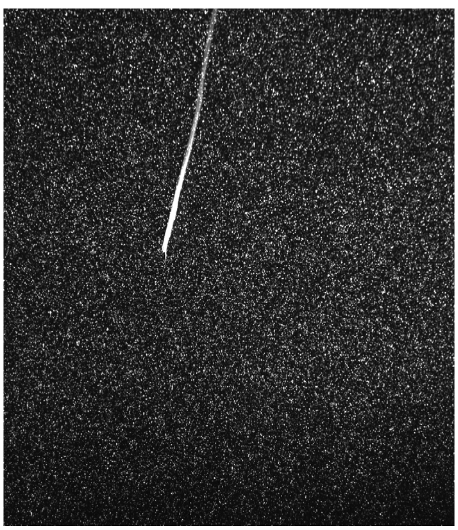
APPROACH

We have carried out rigorous tank testing of the turbulent and optical quantities measured by the OTS and direct compared with standard measurements. Among them we have carried out:

- Using a set of traversing fast thermistors (FP07) we have carried out measurement of temperature dissipation spectra and temperature dissipation rate
- We have carried out a 2D PIV flow measurements to obtain energy dissipation rates, instantaneous flow velocity and flow shear.
- The 0.5 and 1000 μm particulate properties such as VSF were measured by nephlometer and verified the VSF by Mie calculations.
- Concurrently with above measurements we have carried out optical characterization of the flow and particles in the turbulent tank obtaining: temperature dissipation spectra, flow speed, flow shear and particle VSF.

WORK COMPLETED

Measurments of turbulent kinetic energy dissipation and the mean flow speed.
Using 2D PIV we have measured and calculated energy dissipation rates for the turbulent flows concurrent and collocated (Figure 1) with the OTS.



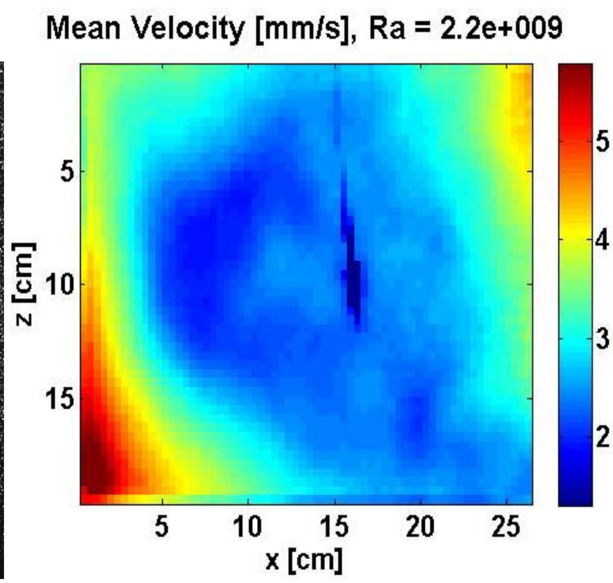


Figure 1

*A- **Sample PIV image showing flow seeded with 10 μu particles and FP07 fast thermistor in the cell interior. Pairs of such images are cross correlated to obtain velocity flow fields for the tank transect.***

B- ***Time averaged (3 min) velocity at Ra=3.3 10^9***

Method
With the velocity flow fields resolved by PIV, we have estimated of the TKED rates
In order to obtain the TKED rate from equation the out of plane parameters (velocity and direction along the y-axis) must first be replaced with equivalent forms of the in-plane parameters (velocity and direction along the x-z plane).

After some manipulations and in terms of the measureable 2D parameters u, w, x, and z the TKED can be estimated from PIV measure velocities as:

$$\varepsilon = 3\nu\left\{\frac{4}{3}\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2 + \left(\frac{\partial u}{\partial x}\frac{\partial w}{\partial z}\right)\right] + \left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial w}{\partial x}\right)^2 + 2\left(\frac{\partial u}{\partial z}\frac{\partial w}{\partial x}\right)\right\}.$$

Here, ν is the kinematic viscosity, x the horizontal direction along the axis of the PIV light sheet, z the vertical axis of the sheet, and u and w the corresponding horizontal and vertical velocities, respectively.

Measurments of temperature spectra and temperature dissiaption rate.
Spatial temperature fields were also obtained via a set of three fast thermistors (FP07) connected to a motorized stage. The thermistors were spaced a set distance apart horizontally, along the x-axis, parallel to the PIV sheet and profiled a horizontal transect of the tank centerline, along the y-axis, as seen in Figure 2. The speed of the motor controlling the thermistors was varied according to the strength of the turbulent flow. From these time series of spatial temperature fluctuations, the spatial temperature spectra are determined. These spectra are used to derive estimates of the temperature dissipation (TD) rate, as discussed below.

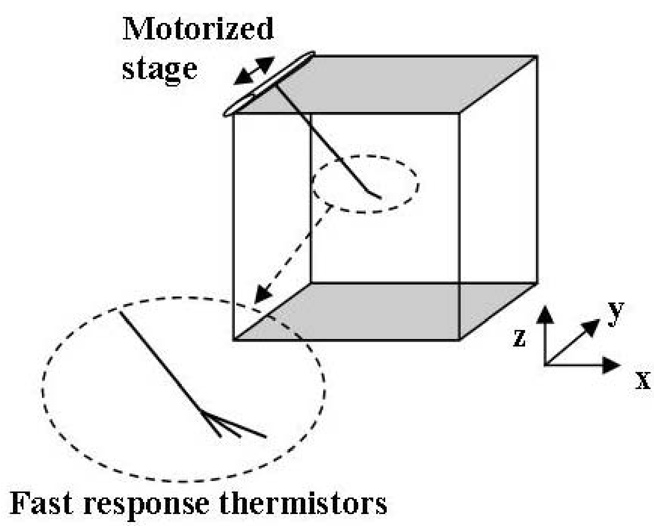


Figure 2. Schematic of profiling fast response thermistors, showing the motor movement along the y-axis, and the thermistor separation along the x-axis.

Method

In general, for homogeneous and isotropic turbulence, the temperature dissipation rate may be expressed as:

$$\chi_\theta = 6D_T \overline{\left(\frac{\partial T'}{\partial x}\right)^2}$$

or

$$.\qquad \chi_\theta = 6D_T \int_0^\infty S(k)dk = 6D_T \int_0^\infty k^2 E_{1\theta}(k)\,dk$$

The overbar denotes a temporal average, D_T is the thermal diffusivity, T' the temperature fluctuation, k the wavenumber, and $S(k)$, $k^2E_{1\theta}(k)$ the theoretical one-dimensional thermal gradient spectrum.The one-dimensional Batchelor spectrum in equation is given by

$$S(k) = \chi_\theta \frac{\sqrt{2q}}{2k_B D_T} S_N(K)$$

.

Here, q is a universal constant, taken to be $2(3^{1/2})$, K the dimensionless wavenumber, given by $K = \sqrt{2q}\, {}^{k}\!/_{k_B}$, and k_B is the Batchelor wavenumber, given by the inverse of the Batchelor length scale: $k_B = {}^{1}\!/_{L_B}$. $S_N(K)$ is the normalized spectrum:

$$S_N(K) = K\left[e^{-K^2/2} - K\int_K^\infty e^{-x^2/2}dx\right]$$

. By fitting the Batchelor spectrum, $S(k)$, to the measured spectrum, equation 4.1b can be rewritten to estimate χ_θ from a combination of the measured spectrum and corresponding fit:

$$\chi_\theta = 6D_T\left[\int_0^{k_L} S(k)dk + \int_{k_L}^{k_N} k^2E_{1\theta}(k)dk + \int_{k_N}^\infty S(k)dk\right],$$

where k_L and k_N are the lowest and highest of the range of wavenumbers over which $S(k)$ was fit to $k^2E_{1\theta}(k)$.

RESULTS

Energy dissipation rates:

The PIV measured dissipation is weaker in the quieter core and increases near the boundaries across the higher velocity shear. This is consistent with previous observations, that the time-averaged TKED rate has two main contributions: the thermal plumes that dominate the bulk region, and the mean temperature gradient that is concentrated in the thermal boundary layers, and which increases with increasing Rayleigh number – Figure 1 and Figure 3

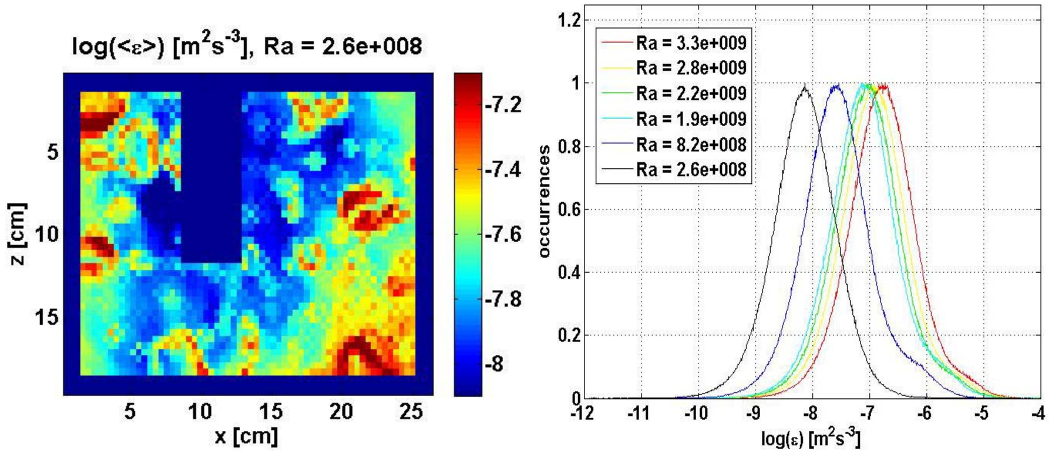


Figure 3.
A -Time-averaged TKED rate (m^2s^{-3}) map at Ra=2.6*10^8
B- histogram of TKED rates for different Ra numbers. Note the TKED distribution follows Gaussian around the TKED peak.

In order to provide sufficient estimation of the TKED rate, care must be taken in choosing the window filter size used for cross correlation of the PIV images. Larger windows, such as 64 and 128 square pixels have sufficiently low noise levels, but poorer resolution, while smaller windows, such as 16 and 32 square pixels, provide measurement of the smaller relevant turbulent scales, but are also plagued by higher noise levels. Analysis was therefore carried out a number of window sizes to obtain the optimal TKED estimate.

Temperature spectra:
One-dimensional temperature gradient spectra, $E_{1\theta}(k)$, were obtained by Fourier transforming each measured temperature transect. These measured spectra were then fit with the Batchelor spectra from equation as presented in Figure 4. The thermistor measured temperature spectra become noisy at high wave numbers – where electronic noises and a finite thermistor response results in increasing noise contribution - Figure 4.

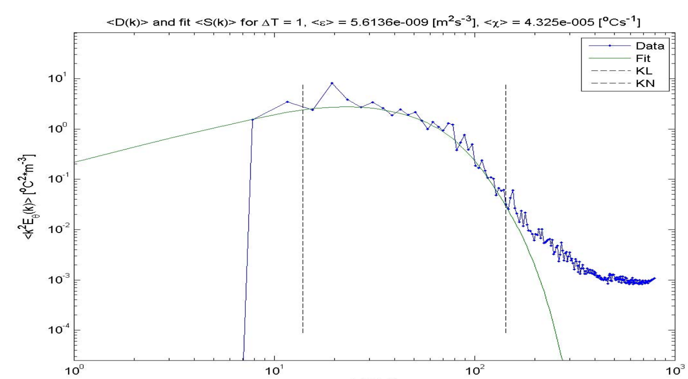


Figure 4. Thermistor measured one-dimensional temperature gradient - $k^2E_{1\theta}(k)$, spectra (blue line) and corresponding Batchelor - $S_N(k)$ spectra fit (green line).

Each spectral dissipation (obtained at fixed tank Rayleigh number) was used to determine the corresponding turbulent thermal dissipation rate. The TD rate was found by integrating the measured dissipation spectra over the measured wavenumber range, and using the fitted dissipation spectra to extend the integration to all wavenumbers, as expressed in equation for χ_θ.

Comparison of optically measured temperature spectra with fast thermistor measured temperature spectra.

We are in process of comparing the optically determined temperature dissipation spectra with the FP07. The Figure 5 presents the comparison between OTS measured 1 second data set and 20 min long thermistor data. Since the fast thermistor becomes noisy and high wavenumbers we have used a ensemble of 20 minute long thermistor measurements and carried out with varied between 2 cm/s to 10 cm/s thermistor speed. The optical measurement generated stable spectra over few milliseconds but for stability for each experimental run we have acquired a 1 second worth of data. The results are presented on Figure 5.

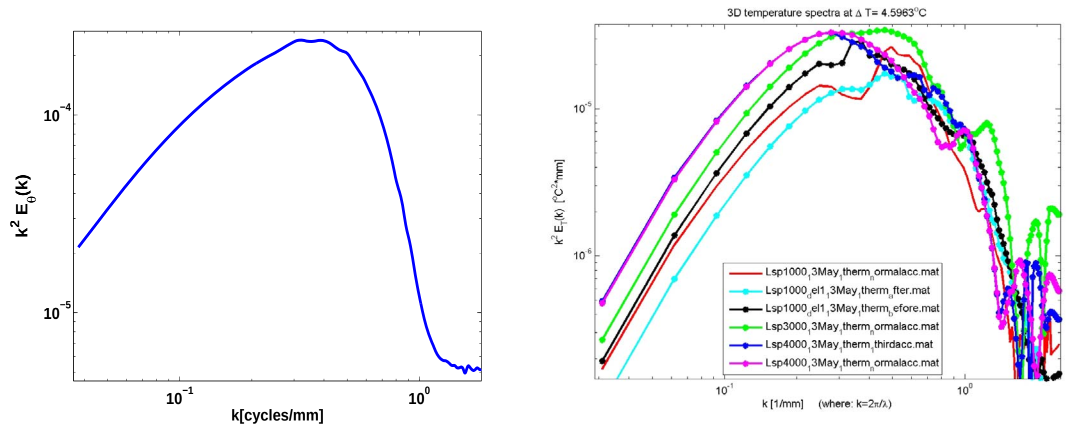


Figure 5. Three dimensional temperature dissipation spectra – $k^2*E_\theta(k)$.
A- The optically measured spectrum - 1 second average
B- Fast thermistor (FP07) spectra, collected at a different thermistor speed and varying between 2 to 10 cm/s each over 20 min time span.

The OTS measured - three dimensional temperature dissipation spectra – $k^2*E_\theta(k)$ compares well with the thermistor spectra – Figure 5. Since the fast thermistor becomes noise at high wave numbers – the effects of that noise are apparent on the Figure 6.

In general the OTS measured temperature spectra are same as the fast thermistor but exceeds the thermistor in accuracy thus allowing for precise temperature and energy dissipation rates from optical measurements.

Particle turbulence interaction.

The goal of this part work is to develop greater understanding of particle dynamics in a turbulent flow. To that end we have carried out a laboratory experiment where a few large particles of know size were inserted into a turbulent flow. The aim was to concurrently characterize particles, temperature dissipation rates and visualize coherent turbulent structures. An example form such experiment is presented in the Figure 6.

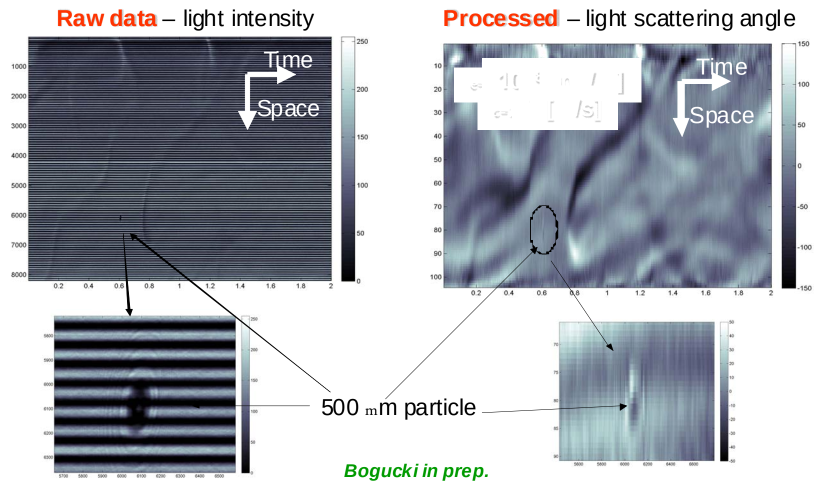


Figure 6. Raw (intensity) and processed (light scattering angle) images acquired for a controlled flow with a single 500 m particle. The images were acquired over ~5 cm aperture in 5 minutes.

The single particle is visible in the raw data surrounded by its diffraction rings. The scattering angles associated with the 500 μm particle and characterized in terms of the particle VSF show rapid VSF decrease at scattering angles of around 80 μrad.

This is consistent with the Mie calculations for 500 μm particle (Figure 7) which predict steep VSF decrease at around O(80 μrad).

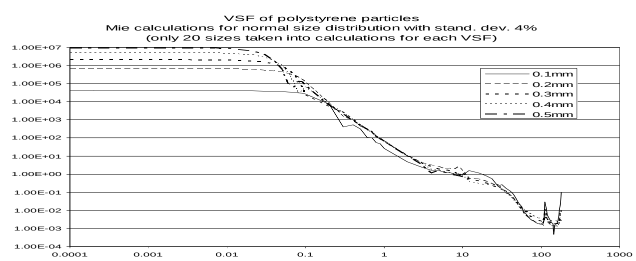


Figure 7. Nearforward VSF for different particle sizes ranging from 0.1 m to 0.5 mm.

In addition we noticed a frequent appearance of hairpin vortices (Figure 6) before or after particle observations.

IMPACT/APPLICATIONS

- The optically measured temperature spectra (OTS) are consistent with the ones obtained from the fast thermistor (FP07).
- The optical/wavefront measurments yield a correct amount of scattering for larger particles thus allowing for concurent characterization of larger particles and background turbulent flow.
- OTS has matured now to become an oceans sensor to optically measure turbulence concurrent with large particulate optical properties, large particle fluxes and the water column refractive index fluctuation spectra.

PUBLICATIONS

[1] D. J. Bogucki, J. Piskozub, M.-E. Carr and G. Spiers. Monte Carlo simulation of propagation of a short light beam through turbulent oceanic flow. Optics Express. 2007, 13988-13996 . [published, refereed]

S. Woods, W. Freda, J. Piskozub, M. Jonasz, D. Bogucki. “Laboratory measurements of light beam depolarization on oceanic turbulent flows. [in press, refereed]

Conference presentations:

S. Woods, D. J. Bogucki, W. Freda. Effects of large particle and turbulent scattering on wavefront sensor measurements of the volume scattering function. Ocean Optics, Italy 2008.

D. J. Bogucki, S. Woods, W. Freda. Turbulent oceanic flow – an optically active medium. Ocean Ocean Optics, Italy 2008.

W. Freda, S. Woods, D. J. Bogucki, M. Jonasz. Depolarization of the near-forward scattered light by turbulence. Ocean Optics, Italy 2008.